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A NEW APPROACH TO MILLIMETER-WAVE COMMUNICATIONS. (U)

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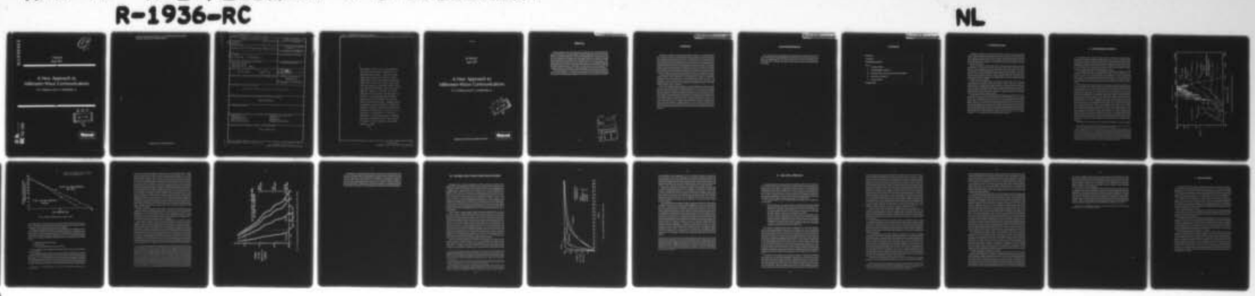

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N. E. Feldman and S. J. Dudzinsky, Jr.

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An argument for the use of the millimeter wave band for military earth-satellite communications systems. Important advantages accruing from this use are larger bandwidths and narrower antenna beamwidths, which would reduce interference and ameliorate the frequency management problem while also improving covertness and resistance to jamming. However, millimeter waves are particularly susceptible to attenuation by rainfall. A new approach for designing around the rainfall problem is described and its benefits discussed. Outages caused by rainfall can be avoided by a variety of automatic switching schemes, by using techniques for increasing jam resistance, or by switching to a satellite in a different direction. The concept proposes switching only high-precedence traffic and only for the duration of the outage at the ground terminal. (JDD)

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PREFACE

The development of the new approach to millimeter-wave communications described in this report was supported by The Rand Corporation with its own funds. This work, which drew heavily on Defense Advanced Research Projects Agency and Air Force sponsored millimeter-wave and submillimeter-wave research, initiated Rand involvement in the application of millimeter waves to communications. This study formed the basis for two current Rand projects—one for the Defense Communications Agency entitled "Advantages of Frequencies Above 8 GHz for Military Satellite Communications: An Overview," and one for the Air Force entitled "An Analytical Basis for the Design of Usage-Compatible Communications Systems."

This report should be of interest to all three services, to government agencies concerned with military or commercial communications, and to all those concerned with spectrum planning and management and future communications technology.

SUMMARY

Designers of military communications satellite systems are constantly seeking ways to improve physical [1] and electronic [2-5] survivability and to alleviate spectrum congestion and interference [5,6]. Use of the physically small components and the large bandwidths potentially available in the millimeter-wave band can help to accomplish these aims. Small high-gain antennas at millimeter wavelengths permit proliferated mobile terminals, thus enhancing physical survivability. The greater antenna directivity and the greater bandwidth over which the signal can be spread at these higher frequencies enhance covertness and resistance to jamming, and thus improve electronic survivability. Nevertheless, communicators have been reluctant to exploit millimeter waves, primarily because of concern over outages due to rain.

The approach described in this report is based on the hypothesis that availability requirements for many applications of communications systems are excessively stringent. Outages caused by rain in the millimeter-wave band may prove to be acceptable in many circumstances and may be justifiable when the delays and outages caused by other factors are considered. This hypothesis needs to be verified through further study and analysis.

In the case of high-precedence traffic for which the additional outages caused by heavy rain are unacceptable, the approach described here would avoid the outages through a variety of automatic switching schemes, e.g., by switching to other available communications facilities operating at frequencies that are relatively unaffected by rainfall (frequency diversity). Alternatively, the approach could be implemented by using many of the techniques considered for increasing jam resistance, such as switching to higher transmitter power, to a higher gain satellite antenna, or to a lower information rate; or it could be implemented by switching to another millimeter-wave band satellite in a different direction so as to avoid the small, high rain rate cells within a rain storm. Regardless of technique, this concept proposes switching only high-precedence traffic and only for the duration of the outage at the ground terminal.

ACKNOWLEDGMENTS

The authors wish to acknowledge the encouragement provided by W. B. Graham, Head of Rand's Engineering Sciences Department, the numerous helpful comments and suggestions of C. M. Crain, and the careful review of the report by E. Bedrosian and A. L. Hiebert. The table on cloud and rain models was generated by R. R. Rapp.

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I. INTRODUCTION

Designers of military communications satellite systems are constantly seeking ways to improve physical [1] and electronic [2-5] survivability and to alleviate spectrum congestion and interference [5,6]. For many military applications, millimeter waves may offer the best means for accomplishing these aims. In addition, the large bandwidths potentially available in the millimeter-wave band would provide for a variety of new services.

The term millimeter waves strictly refers to the spectral region between 30 GHz and 300 GHz, i.e., between 10 mm and 1 mm, but is often used to include the region between 10 and 30 GHz. The concepts discussed in this report apply to the entire region between 10 and 300 GHz. Most communications today take place in the lower part of the microwave band, below 10 GHz. In the millimeter-wave band, the potential spectrum available for military communications is more than a hundred times larger than is presently allocated in the 8-GHz band for the current Defense Satellite Communication System (DSCS).

Unfortunately, millimeter-wave communications links suffer severe attenuation during intense rainfall, which often results in outages. This report shows the magnitude of the rainfall problem and explains how the practical use of millimeter waves has been restricted by this problem. A new approach for designing around the rainfall problem is described and its benefits discussed. While the emphasis is on earth-to-satellite links and military systems, the approach applies to terrestrial links and to commercial systems as well.

Delays should not be treated differently from outages since the effect of a message delay on the outcome of a crisis will be the same as the effect due to an outage. Only if the combined delay and outage time in a millimeter-wave system were greater than in current military communication systems would there be any degradation relative to current systems. It should be noted that this approach is based on an unproved hypothesis that needs to be verified by gathering further experimental data on propagation and on delays and outages in communications systems due to factors other than rainfall. Analysis of these data should provide a basis for designing millimeter-wave communications systems which are neither over- nor underdesigned, i.e., what might be called usage-compatible systems.

II. ATMOSPHERIC EFFECTS

The millimeter-wave band is the last frontier for radio-wave communications through the atmosphere, as demonstrated by the curve for a clear atmosphere in Fig. 1, which shows sea-level atmospheric attenuation. In the submillimeter band, which lies between 1 and about 0.03 mm, attenuation through a clear atmosphere [7,8] is exceedingly high because the radio-wave energy is absorbed by water vapor. Hence, it is very unlikely that communications systems that operate through the atmosphere ever will be designed in the submillimeter region.

The attenuation through a clear atmosphere drops off for wavelengths in the IR and optical bands, that is, for wavelengths shorter than 0.03 mm. However, it can be seen from Fig. 1 that clouds and fog cause additional or "excess" attenuation above that of a clear atmosphere; such attenuation [9,10] can be very high in the IR and optical bands. Clouds and fog present severe problems to designers of laser communications systems because they persist over large areas for long periods of time.

While high-data-rate optical links from satellites to high-flying aircraft may prove useful since there is little cloud cover above 30,000 ft, any single high-data-rate optical link to a sea-level earth station will be unavailable about 10 to 90 percent of the time [11].[1] Use of path diversity by means of three to five sites separated far enough apart so that cloud cover or fog is sufficiently decorrelated to assure a high probability of one cloud-and-fog-free line of sight is another means of bypassing cloud and fog problems in the optical band. Where these solutions are precluded, there may still be the possibility of useful communications because most of the attenuation is due to scattering [12-15] rather than to absorption.[2] On the cloudiest of days it is not much darker outside than on a clear day since the light level is still about 20 percent. This is only a 5-dB decrease. To recover the multiply scattered laser energy after it has passed through a thick cloud requires a large array of elements; each element must cover a much larger angle than is the case when clouds are not present, and the received energy can only be noncoherently summed. While such a scheme is technically feasible, it is of doubtful utility considering the alternatives. However, in special cases such as communications to submerged submarines [16], such systems may be justified despite the high cost for a low-data-rate link because they would provide a unique and vital communications capability.

Fortunately, clouds and fog have a relatively small effect on earth-to-satellite

[1] If a low dissipation mechanism for laser tunneling through thick, dense clouds were to be discovered, i.e., self-induced transparency, this conclusion might radically be changed.

[2] The attenuation coefficients for cloud and rain in Fig. 1 (which more properly should be called extinction coefficients) are based on Mie single-scattering theory and thus neglect multiple scattering. As a result, they strictly apply only to coherent transmission through the medium. More important, they show only total extinction; they do not separate it into its absorption and scattering components. For wavelengths less than about 2 μm, almost all of the extinction due to clouds results from scattering [9], and it is this fact which makes it possible to conceive of optical communication channels that depend on the phenomenon of multiple scattering. Such channels are not possible in the submillimeter band, where the high extinction in a clear atmosphere is due primarily to absorption by water vapor, and where the high extinction by clouds and fog is due primarily to absorption by water droplets.

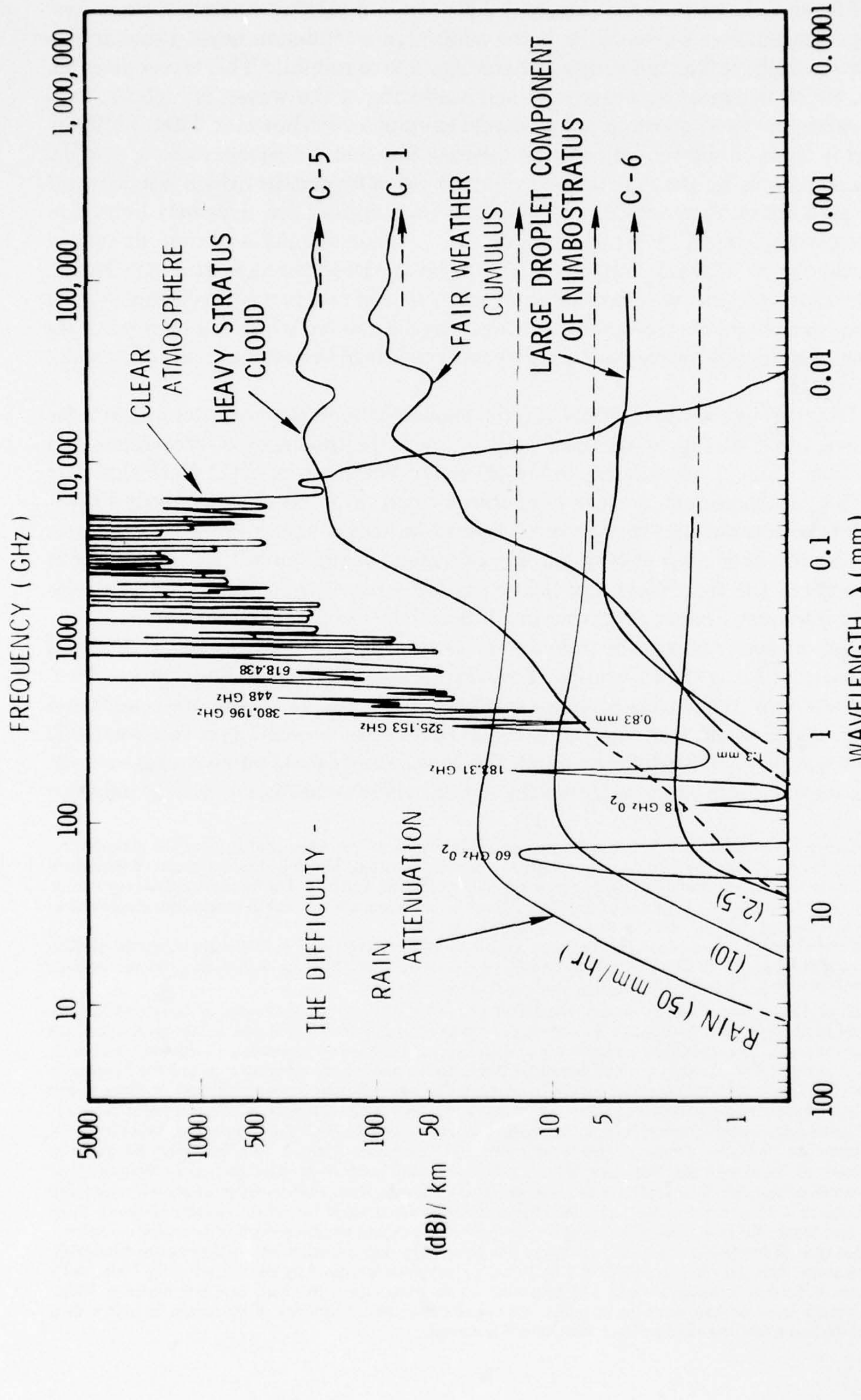

Fig. 1—Summary of sea-level atmospheric attenuation

millimeter-wave links; even a thick, heavy stratus cloud causes only a few dB of attenuation in this band, except at very low elevation angles.

Figure 1 shows that the principal difficulty in designing communications systems at millimeter wavelengths is the additional attenuation beyond that in the clear atmosphere (i.e., the excess attenuation) due to rainfall.[3] This excess attenuation, which is caused by absorption and scattering of the waves, is high for high rainfall rates. Two important points should be emphasized, however. First, while the effect is large, rain attenuation is not a strong function of frequency above 70 GHz. Second, high rain rates, say in the neighborhood of 50 mm/hr (which would result in a path attenuation exceeding normal system margins), are extremely limited in their coverage, such as a kilometer or two in diameter and a minute or two in duration; such high rain rate cells tend to be scattered throughout a rain storm. While most readers would probably consider 2.5 in. of rain in a day a downpour, this corresponds to a 24-hr average rain rate of only 2.5 mm/hr, which is a light rain rate as far as millimeter-wave systems are concerned since the attenuation is at most 2 to 3 dB/km.

To appreciate weather effects, it is not enough to know their relative magnitudes as shown in Fig. 1; it is also necessary to know the frequency of occurrence and duration. Table 1 shows such information for Washington, D.C.[4] Note that fair weather, characterized by clear to scattered cloud cover, occurs only about 40 percent of the time during a typical year. Thus, while heavy cloud cover (with or without rain) is present 60 percent of the time, moderate to heavy rainfall occurs only about 4 percent of the time. Note that heavy rainfall, greater than 15 mm/hr, is a relatively infrequent event, occurring much less than 1 percent of the year.

Not only is it important to know the percent of time outages occur, it is also necessary to know their duration. The distribution of fade durations for two locations and two frequencies is shown in Fig. 2, from Ref. 19. These are conditional outage distributions that apply only if it is raining; the probability of rain was 0.052 for New Jersey and 0.085 for England. The New Jersey data show an average outage duration of 7.7 min based on 15 months of data, whereas the data from England show

[3] Figure 1, based on Refs. 7, 9 and 10, is a universal curve in the sense that it gives the attenuation per unit length rather than for a specific path at a specific location. There is a vast amount of literature on atmospheric attenuation for the clear atmosphere, clouds, fog, and rain. For an excellent survey article on the role of rain—the dominant effect at millimeter wavelengths—in earth-to-satellite communications, see Ref. 17, which contains extensive references.

To place the ordinate scale in Fig. 1 in perspective, note that a typical system margin on earth-satellite links would be about 10 dB; this has to be allocated among such items as deviation in power output, antenna pointing, receiver noise figure, and path attenuation.

[4] Table 1 was constructed by arbitrarily defining five types of weather (there are, of course, an infinite number of possible weather states), thus conveniently grouping similar situations. It also gives the cloud types that would be reported by an observer and an estimate of the corresponding Deirmendjian models (Refs. 9 and 18). The ranges for cloud base and thickness in meters are estimates, as are the heights to which the rain portion of the model should be carried. The rainfall rates are approximately at the upper and lower quartile of the daily rain amounts. This is probably a fair estimate of "typical" rain rates for the situation described. The last column presents estimates of the frequency of the weather types by hour; it is based on 11 years of data at the Washington, D.C. National Airport. The frequency for clear to scattered clouds, 40 percent, was derived from a table of cloud cover; it is based on hourly reports of the occurrence of less than four-tenths of the sky obscured by clouds. Rain, drizzle, snow, or showers occurred approximately 12 percent of the time. Hourly rain data were divided into three classes: showers, light rain, and moderate rain. The remaining 48 percent was assigned to the broken or overcast category.

This type of breakdown can only estimate the frequency and duration of weather states hindering propagation. Rainfall *rates* in excess of 1 to 2 mm/hr are always caused by convective cells. These cells are only a few km in diameter and will pass over a rain gauge (or a receiver) in a few minutes. If the distribution were broken down to minutes instead of hours, the frequency of moderate to heavy rain would decrease but the median rain rate would increase.

Table 1

Data on Cloud and Rain Models for Washington, D.C.

Cloud Type and Model	Cloud Base (m)	Thickness (m)	Rain Height (m)	Rain Rate (mm/hr)	Frequency of Occurrence (percent)
Clear to scattered clouds; fair weather cumulus, fracto-stratus [C−1][a]	1000−2000	50−100			40
Broken to overcast clouds; stratus, altostratus, cumulus congestus [C−5][a]	1000−2000	500−1500			48
Thick overcast clouds with light rain; nimbostratus, altostratus [2 x (C−5) + (C−6) + 1/3 (R−10)][a,b]	500−1000	3000−4000	2500−4000	1	4
Broken to overcast clouds with showers; cumulo-nimbus, cumulus congestus [2 x (C−5) + (C−6) + 1/2 (R−10)][b]	1000−2000	4000−7000	4000−8000	2	4
Thick overcast clouds with moderate to heavy rain; cumulonimbus, nimbo-stratus, altostratus [2 x (C−5) + 2 x (C−6) + (R−10)][b]	100−500	5000−7000	4100−6500	10 >15	4 $\ll 1$

[a]See Fig. 1 and definition in Ref. 9.

[b]R−10 refers to the 10 mm/hr rain curve shown in Fig. 1.

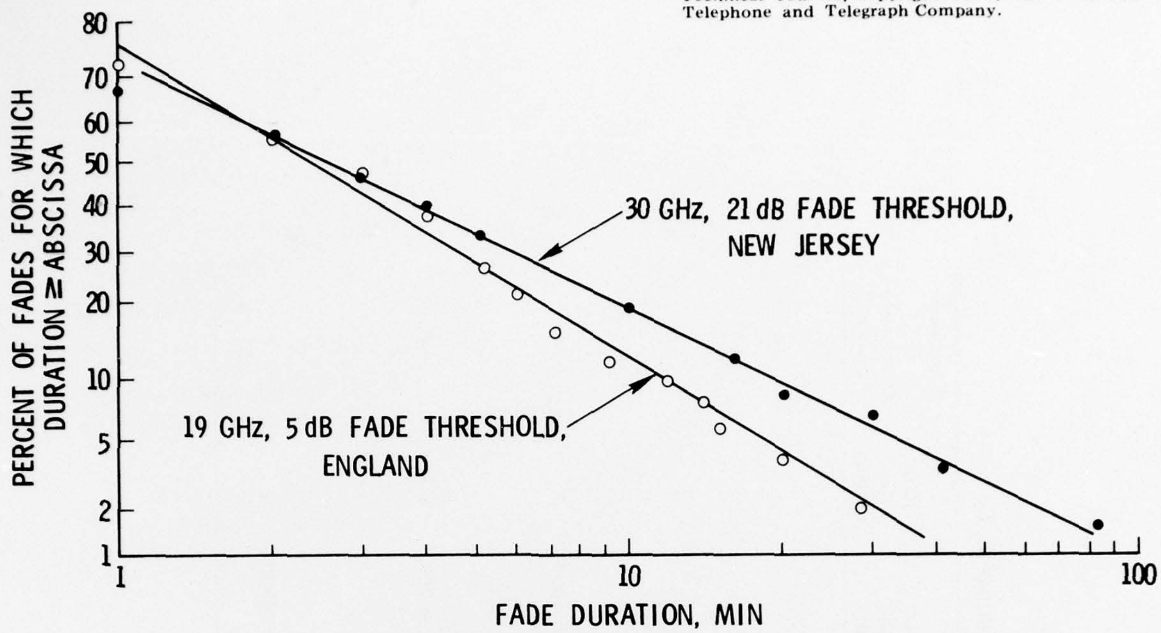

Fig. 2—Lognormal distributions of fade duration

an average outage of 4.4 min based on 12 months of data. Note that 25 percent of the rain outages last less than 1 min and that durations of greater than 10 min are infrequent, i.e., less than 20 percent of the rain outages.

Traditionally, communications systems are designed for an availability or reliability of 99.9 to 99.999 percent. These availability standards are typically set by specifications written by procuring agencies. A 99.999 percent availability represents a total or cumulative outage on the order of 5 min/yr. There are three classical solutions to achieving these high availabilities which can be used alone or in combination:

- Sufficient transmission margin.
- Path diversity.
- Close repeater spacing for terrestrial links.

To what extent are they applicable to millimeter-wave systems in the presence of severe rainfall?

The traditional approach to achieving these very high availabilities by providing high transmission margins suffers from the fact that the required margins can be very high, e.g., 50 to 100 dB. While current satellite system margins are about 10 dB, experimental measurements of excess rain attenuation of 50 dB or more at both 20 and 30 GHz have been made at several locations;[5] the primary reasons they have not been recorded at more locations are insufficient dynamic range or long response

[5] Reported at the 1975 EASCON meeting by L. J. Ippolito of the Goddard Space Flight Center, Greenbelt, Md.

time of the measuring equipment. Path diversity can be implemented by a single satellite working with a number of interconnected ground stations or by a single ground station working with a number of interconnected satellites. The typical space diversity technique (whether described as path or as site diversity) uses two or more earth stations placed far enough apart so that when there is a heavy rainfall at one site it will not be likely to extend to one of the alternate sites. In present designs, the use of space diversity increases the ground segment cost more than two times because of the high costs of additional earth stations and land lines. Furthermore, the satellites are tending to become a small part of the total investment in recent systems, thus making the ground segment cost even more important. In the case of terrestrial terminals, another traditional approach would be to use close repeater spacings—for millimeter waves perhaps only 1 to 2 km apart. This requires about 25 to 50 times as many repeaters as are needed for microwave frequencies. (Worldwide, the average spacing of microwave repeaters is about 50 km [20].) Although each repeater is much cheaper than those used in conventional microwave relays, such as the TD-2 or the TH, the overall cost per channel would be higher. These traditional approaches are either expensive or just plain impractical in the millimeter-wave band.

To gain a better understanding of what is involved in attempting to provide sufficient transmission margin, consider Fig. 3. This figure shows the attenuation distribution over an earth-to-satellite path for a full calendar year (1970). It is an example of a fairly high rainfall location in the United States—Rosman, North Carolina. The curve for 15.3 GHz represents data taken using the ATS-5 geosynchronous satellite and an earth station receiver at Rosman.[6]

For a satellite link at 94 GHz at Rosman, 99.999 percent availability requires a margin of almost 70 dB to account for atmospheric effects. If, however, one were willing to accept a reduced availability of, say, 99 percent, it would be possible to operate with a margin of less than 20 dB, as indicated by the dashed line in Fig. 3. An important point to note is that the curves for all frequencies higher than 94 GHz would lie to the left of the 94-GHz curve because of the flattening out of the rainfall effect mentioned earlier. A second important point is that all of these curves tend to converge as the availability requirements are lowered. Therefore, at this particular location, a 20-dB margin would ensure 99 percent availability for frequencies throughout most of the millimeter-wave band (excluding the oxygen and water vapor absorption bands). Thus, by simply reducing the availability requirements, one can avoid most of the expense involved in the traditional design approaches.

[6] To date, these ATS-5 data represent the best available long-term statistics on attenuation at frequencies above 10 GHz using a satellite, since the ATS-6 was used only on a call-up basis during rain. (It will be some time before better long-term data are available from the COMSTAR satellites.) The 15.3-GHz curve of total atmospheric attenuation in Fig. 3 is an estimate for the calendar year, taken from Fig. 8-13 of Ref. 21. The curves for 31.65 GHz, 50 GHz, and 94 GHz were calculated from the 15.3 GHz curve. The 31.65 GHz curve was calculated by Ippolito [21], while the 50 GHz and 94 GHz curves were calculated by the authors, based on the Hogg data of Fig. 3 of Ref. 10, which plots rainfall attenuation in dB/km per mm/hr as a function of frequency. Admittedly, it is considered risky and rather unreliable to utilize attenuation measurements at one frequency to infer values at another frequency. This is evidenced by the fact that simultaneous measurements at 15.3 and 31.65 GHz using ATS-5 showed attenuation ratios at the two frequencies varying between about 2:1 and 3.5:1 at high attenuations (Fig. 8-3 of Ref. 21). The reliability of such calculated results is lessened by the assumption that the attenuation rates are independent of rainfall rate and type. These may be on the same order as the range of variation from one storm to the next in the same year, so that the calculated curves may roughly approximate the mean distribution over a long term, i.e., over a 30-year set of distributions. In spite of these inaccuracies in the calculated curves, it is felt that they are sufficiently accurate for the purposes of the present discussion.

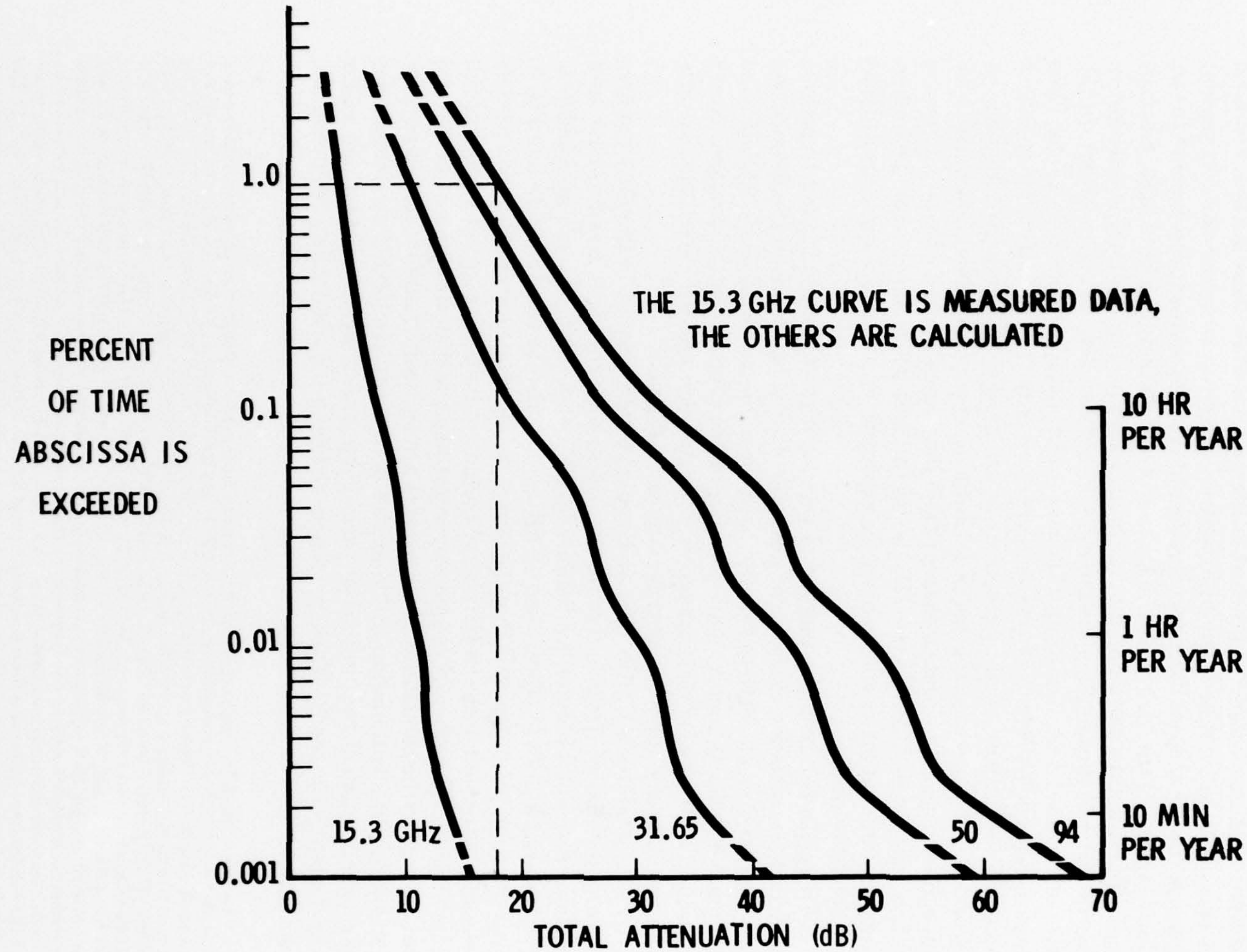

Fig. 3—Attenuation distributions for calendar year 1970 at Rosman, North Carolina

The question is: Could the bulk of military users (who are on the surface of the earth) live with cumulative rainfall outages of 1 percent or more? Even if they could, would the durations of these outages be acceptable? Our hypothesis is that the answer to both of these questions is yes. Given all of the other types of end-user to end-user delays and outages experienced by users of today's military communications systems [22-27], outages due to rainfall at millimeter wavelengths will probably be small in comparison. This is discussed in more detail in the following section.

III. CRITERIA FOR USAGE-COMPATIBLE SYSTEMS

Although we do not have an abundance of data, we do have an inkling of the kinds of delays and outages that military users are experiencing with current communications systems. For example, from a survey made last year of outgoing access (availability of an outgoing line) on the military voice network (AUTOVON) at SAMSO (AFSC), which was limited to 33 outgoing lines, typical blockages were found of two to three 10-min intervals per day between 8:00 and 9:00 a.m. For as many as four to five days per year, there were blockages lasting three to four hours per day. Based on a three-month survey ending July 31, 1973, a report to the Congress on inward access on AUTOVON [25] showed that out of 390 locations, 258 or 66 percent failed to meet the objective for inward grade of service established by the Joint Chiefs of Staff (95 percent availability for all inward access lines during the busiest hour of an average business day). These data are for routine traffic. Thus, present typical military AUTOVON users have to accept appreciable delays due to peak loading.

Figure 4 shows a sample of data for high-precedence message traffic as well as for routine traffic, via the TACSAT satellite, from various locations—mostly from the U.S. mainland to a ship in the Pacific.[1] The cumulative delay times for the four categories of communications precedence shown here represent the interval between the assignment of a date/time group at the sender's communications center and the arrival of the message at the communications center on board ship;[2] the delays do not include message handling times outside of the communications centers. The curves are for an average day during several months of operation. The median delay for flash traffic, the highest precedence, is on the order of 20 min; this means that the average user with flash precedence had to wait 20 min for his message to get through. The delay is greater than one hour for 5 percent of the flash messages, yet the flash category represents only 3 percent of all messages. These are long delays but nevertheless represent a large improvement over all previous systems, such as HF and manual message-handling satellite modes.

This 20-min delay suffered by a flash user at the median is equivalent to his having to accept a 20-min outage due to rain in a millimeter-wave system with no other sources of outage. For a median user at Rosman to experience a 20-min delay at 94 GHz in a satellite system with 20 dB of rain margin would require annual rainfall in excess of 860 in.[3] Nowhere in the world does the annual rainfall equal

[1] These data were originally collected by Commander W. H. Curry, Jr., USN, while assigned as the 7th Fleet Communications Officer. His current address is: Commanding Officer, Naval Command Unit, Washington, D.C. 20390. The data, which are used with his permission, were originally plotted as a time distribution of events. They have been replotted as a cumulative distribution for this report. Causes of outages and delays in TACSAT are described in some detail in Ref. 23, which points out that the time to correct merely one common type of trouble—uplink power imbalances—ranges "from a few minutes to several hours."

[2] It is interesting to note that, by and large, routine traffic incurred somewhat shorter delays than higher precedence priority traffic. This may have been because the senders of routine messages filed their messages during nonprime time, i.e., when the system was lightly loaded.

[3] The Rosman data of Fig. 3 show that a 20-dB margin is exceeded about 1 percent of the time at 94 GHz. Rain rate data for the full calendar year 1970 for Rosman (given in Ref. 21) show that a rain rate of 2.5 mm/hr would be exceeded about 1 percent of the time. Thus, a rain rate in excess of 2.5 mm/hr results in an attenuation at 94 GHz that exceeds the 20-dB margin. Assume a rain rate histogram in

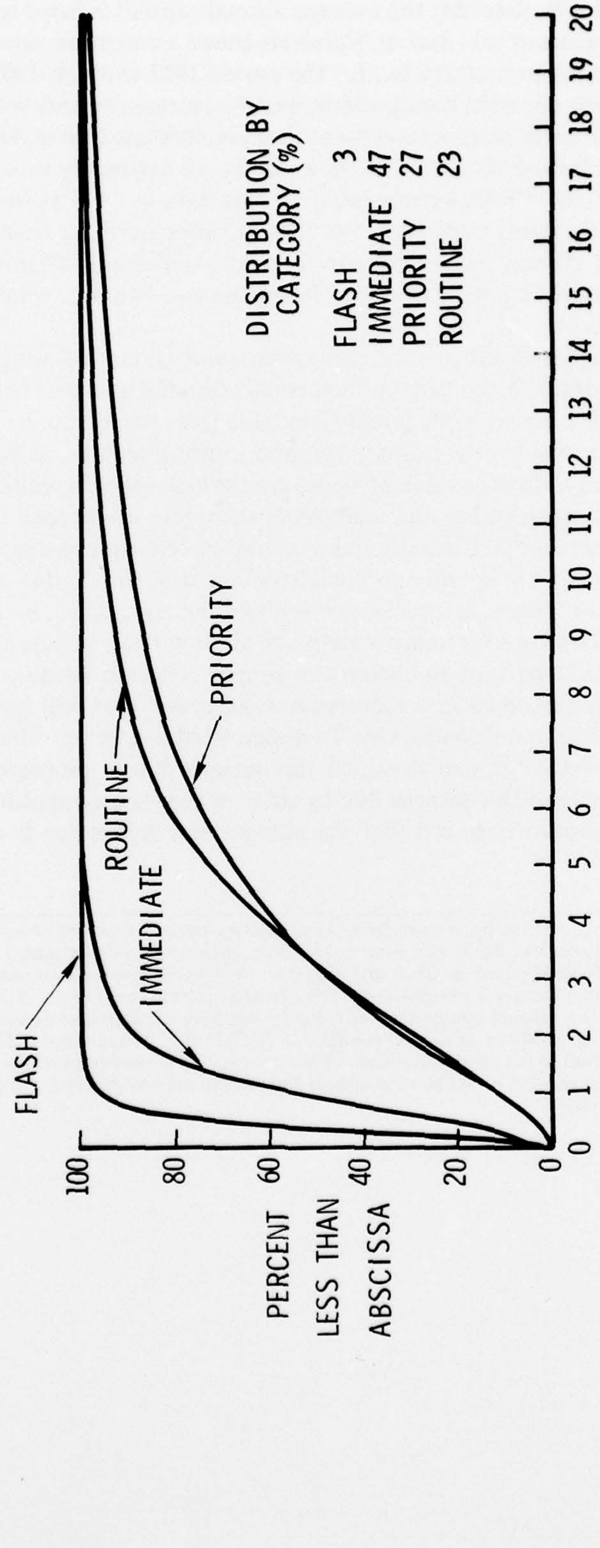

Fig. 4—Automatic satellite message transfer time

or exceed 860 in.; this corresponds to 2.4 in. of rainfall every day at a steady rain rate of about 2.5 mm/hr. The wettest spot in the world is at Waialeale, Hawaii (on the island of Kauai), according to information supplied to the *World Almanac* by the National Geographic Society [28]; the average annual rainfall is listed as 460 in. An examination of 46 years of rain data at Waialeale shows a maximum annual rainfall of 624 in. (and a minimum of 218 in.) for the period 1911 through 1957 [29].

Preliminary fade duration distributions, based on measurements with the ATS-6 satellite using the earth-station receiver at Rosman, indicate that at 30 GHz a fade in excess of 10 dB lasting 20 min or more would be an extremely rare occurrence (see Fig. 12 of Ref. 30). Crude extrapolation of this data to 94 GHz indicates that there would not have been more than two fade durations greater than 10 dB and lasting more than 20 min (one of 57 min duration and one of 27 min) during a five-month measurement period which included the two heaviest rainfall months (July and August).

The data presented on outages and delays represent no more than those readily available to the authors. More data on factors affecting the end-user to end-user or the writer-to-reader time are undoubtedly available from sources such as records of day-to-day operations between military communications centers, as well as from records made during military exercises. These are the types of data required to prove our hypothesis, but aggregation and analysis of such data are beyond the scope of this report. The question is: If traditional availability criteria are discarded, what criterion does one use to select an appropriate outage time for rainfall alone? Such factors as equipment failure, saturation, switching time, processing, handling, decisionmaking, and allowance for improvement are all important in determining that criterion. And it is important to choose the proper criterion because the choice ultimately becomes embodied in a requirement document that will have a strong influence on system cost and complexity. To design what can be considered a usage-compatible system—that is, one in which the outages due to propagation effects alone are comparable to the outages due to other effects and compatible with the application—it is necessary to consider the outages and delays due to all of these factors.

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which it rains at a rate of 2.5 mm/hr or more for 40 min, followed by an interval of lower rain rate that is short compared to 40 min, e.g., 3 to 6 min. Assume that this pattern repeats throughout the year, that messages are uniformly distributed in time, and that the capacity of the communication system is sufficiently great that all messages in the queue are transmitted in the lower rain rate interval. This set of assumptions results in a median outage of 20 min due to rain alone; it corresponds to approximately 2.5 mm/hr $\times$ 8760 hr/yr, or 860 in. of annual rainfall. At 30 GHz, Fig. 3 shows that a 20-dB margin is exceeded about 0.1 percent of the time at Rosman. This corresponds to a steady rain rate of 20 mm/hr. Thus, 7000 in. of annual rainfall would be required for the median user to experience a 20-min outage due to rain alone at 30 GHz.

IV. THE NEW APPROACH

As military demand for communication by satellite continues to grow, say by a factor of 100, present systems will become saturated despite the use of information compression, improvements in modulation, frequency reuse in each satellite, and multiple satellites. In order to handle the same mix of traffic as is now being handled and to allow for the growth of new services, it will be necessary for the military to move to higher frequency bands. As we have pointed out, the millimeter band is not only the most promising but is also the last frontier for communications through the atmosphere. But the system designer must cope with rainfall effects.

Our proposed solution to the rainfall problem at millimeter-wave frequencies has two parts:

- Design millimeter-wave links with lower availability than that prescribed by traditional standards. Earth-to-satellite links with availabilities of 90 to 99.9 percent, and delays and outages due to rain alone of 5 to 30 min, may provide acceptable service for a large number of military users. The bulk of traffic would be carried by the millimeter-wave links.
- Provide a two-tier, automatically switched system to accommodate users who require higher availability. One tier would consist of communications facilities relatively unaffected by rainfall. In many cases this tier would use systems that are already paid for and currently in use (e.g., at HF, UHF, or 8 GHz) or systems already under development. The lower availability millimeter-wave system would be the other tier.

The number of high-precedence users or messages at any one time might be about 1 percent and probably no greater than 10 percent, even in a crisis (especially if the use of the flash category is restricted as the length of the queue increases), and the rainfall outages in a system at any one time are likely to be on the order of 0.01 percent in dry areas to, at most, 10 percent in high rainfall areas. Since these are conditional, independent probabilities, the probability of having to switch to backup or alternate facilities is simply their product. Thus, a two-tier system could provide a very large leverage factor on the lower frequency microwave band—in the range of 100 to 1,000,000—because only as many as one message in a hundred to as few as one message in a million would need to be switched to the backup facilities at any one time. A key point in this concept is that it would provide lower but acceptable reliability for most users at lower cost, and that the traditional 99.9 percent or better reliability would be provided for high-precedence users at higher but not prohibitive cost.

In addition to the possibility of switching to systems at frequencies unaffected by rainfall, there is the obvious possibility of operating at a lower data rate (temporarily serving only the highest precedence category). The two-tier feature of this approach also could be provided by a variety of backup techniques in the millimeter-wave band through a dynamic reallocation of resources from user to user as necessary. For example, it may be possible to provide 20 to 30 dB of additional margin on paths which have high attenuation, but only for the duration of the high attenua-

tion, by pointing a higher gain satellite antenna beam along the path. This eliminates the need for providing the margin continuously for every path. A single communications satellite may be carrying signals from 1000 to 100,000 information sources yet may be in use by only 10 to 1000 stations (fixed and mobile terrestrial, shipboard, and airborne combined). Assuming that all of these stations are 20 to 30 km or more apart (so that the incidence of heavy rainfall is decorrelated), then only 1 percent of the stations at any time may have an excess path attenuation greater than the rain margin. If only 1 percent of these have flash traffic at that time, it follows that a single steerable high-gain antenna beam on the satellite could cope with the excess rain attenuation for all stations having flash messages. To allow for component failures, peak loads, or crises and weather anomalies such as frontal storms or hurricanes, perhaps two to four steerable beams would be desirable. Four or more steerable beams could perhaps provide the extra margin necessary for all user stations. For a system designed with 20-dB margin, and with an additional 20 to 30 dB of margin from the steerable beam, the cumulative probability of a rain outage at Rosman would be at most about 0.1 to 0.01 percent of the time at any frequency in the millimeter-wave band, according to the data of Fig. 3.[1]

Another technique for dynamically compensating for rain attenuation is to increase the power output at both the satellite and the ground station for the duration of the high path attenuation. A 10-dB increase in transmitter power output without sacrificing efficiency is feasible at both ends of the link. Use of this option first (before moving the steerable beam) can reduce the number of steerable satellite beams required.

Another technique that deserves mention is the use of space diversity through a multiple-beam antenna at the ground station. In this concept, a single ground station may communicate with any one of several satellites. Satellite-to-satellite links will be required to assure continuity between some widely separated ground stations. Only severe rainfall from low-altitude close-in clouds (within a few kilometers of an earth station) could cause high attenuation on two paths in significantly different directions.

The advantages of the two-tier approach proposed here are that it exploits millimeter waves without exorbitant costs by accepting their characteristics rather than fighting them; it provides higher throughput and lower median delays for the majority of users because, for the same investment, one can have a higher capacity; and it provides for expanded use of high-information-rate services and for new services because of the large amount of spectrum available in the millimeter-wave band. Finally, by accepting higher, but tolerable, outage levels this approach permits the system designer to emphasize other features of military importance that are inherent in the use of millimeter waves, such as reduced interference, easier antenna stabilization for smaller antennas due to the lower mass,[2] improved physical survivability through proliferated small mobile ground terminals, and improved electronic survivability (jam resistance and covertness).

To place this new approach to millimeter waves on a solid basis will require further work in analyzing statistical data on the end-user to end-user characteristics

[1] Based on one year of suntracker measurements of attenuation at 19 and 30 GHz in New Jersey, the attenuation at 100 GHz has been estimated to exceed 60 dB from 0.01 to 0.1 percent of the time (see Fig. 40 of Ref. 17) and 28 dB for 1 percent of the time, about 8 dB higher than the estimates for Rosman. No good estimate of error is possible for either extrapolation based on present limited data.

[2] However, as beamwidths narrow, antenna pointing becomes more difficult.

and the propagation effects that have already been discussed. Another factor deterring the increased use of the millimeter-wave band is the unavailability of components. The state of the art of component hardware and the prospects for improving hardware availability need to be studied. It is very probable that features important to the military, mentioned above, may be more easily achieved as frequency is increased. If this is true, it is necessary to determine how high in frequency military users should plan to go, how many different frequency bands can be efficiently utilized, and which users will gain the most from moving up in frequency and therefore should be the first to do so. These questions require examination of the full range of potential applications.

This approach should be attractive to low-precedence as well as to high-precedence users. Potential applications include voice and video as well as message traffic, and the approach can be used with small mobile as well as high-capacity fixed stations. For low-precedence voice and two-way video traffic, for example, the ready availability of propagation statistics to the users—plus an outage prediction and detection capability—may be essential. Propagation statistics for the two station locations composing one circuit, i.e., a pair of links, for the appropriate time of year and hour of day and weighted by local weather data, can provide both sets of users with an assessment of the risk of an outage and the probability of an outage of any given duration. If the risk is considered appreciable, contingency planning is possible, e.g., the users could agree to wait for the link to be restored for all outages less than a few minutes and could arrange advanced scheduling of a time for resuming contact to avoid long outages or periods of frequent short outages. Outage detection can reduce user frustration by signaling both users when the link is about to go out and when it is about to become available again, thus minimizing ambiguity. Because millimeter-wave links are likely to be power limited rather than bandwidth limited, the use of lower system margins means that higher capacity can be provided for the same investment. Higher capacity reduces unit cost and also reduces queuing time, which is of dominant concern for the bulk of users. Lower queuing times reduce the need to upgrade the precedence category to the limit the originator can command.

For the highest precedence users, outage prediction may permit automatic switching in advance of the outage and may avoid not only loss of information but perhaps loss of synchronization. Lower cost millimeter-wave systems should be developed with moderate rain margins to facilitate emphasizing other desirable features of far greater importance to the military than very high availability. By moderate rain margins, we mean rain margins on the order of 10 dB in the bands between 20 and 45 GHz—the bands currently being considered for military millimeter-wave satellite systems. For example, Fig. 3 shows that, at Rosman, a 10-dB margin would provide about 99.95 percent availability at 20 GHz, about 99 percent at 30 GHz, and roughly 98 percent at 45 GHz.

Dynamic adaptation to rain attenuation (by switching to higher power levels, for example) in the millimeter-wave band on a path-by-path basis may provide experience applicable to adaptive antijamming systems (since the variables and techniques are similar). Since rain cells move slowly, i.e., at wind velocities, appreciable reaction time should be available for adaptation. Twenty years ago, a demanding communications mode which required rapid and frequent switching was explored experimentally; meteor burst communications [31] was a forward-scatter mode utilizing that fraction of the estimated 10 billion dust-like meteoric particles bombarding

the earth's atmosphere each day which produced useful free electron trails. The meteor burst mode permitted communications between two points 1000 mi apart about 5 percent of the time, each communication burst lasting from 0.1 to several seconds. Adaptive systems for rain attenuation in the millimeter-wave band are likely to require far less frequent switching, and may require a less demanding design relative to today's technology.

So far, we have only discussed dynamic allocation of the rain margin; further advantages may accrue from designing a system with dynamic adaptation. Dynamic adaptation to lower path attenuation or higher transmitter output power than the average is also possible by operating near the demodulation threshold at all times. This permits maximizing information throughput by putting the normal system margin to use,[3] and reduces the queue for high-precedence messages, perhaps eliminating it under normal conditions. Eliminating the backlog in a communications system represents a desirable state of preparedness in advance of any crisis.

[3] Reference 32, on the JANET system, shows that a variable bandwidth system increased throughput by factors of 2 to 3 over a fixed bandwidth system.

V. CONCLUSIONS

It appears that the use of the millimeter-wave band can provide many improvements in military earth-satellite communications systems. For example, the larger bandwidths and the narrower antenna beamwidths reduce interference, and with it the frequency management problem. Small proliferated mobile ground stations increase physical survivability. Large bandwidths and narrow beamwidths also improve covertness and resistance to jamming, that is, electronic survivability.

To obtain these vital features, we must change design standards and accept higher rain outages in the millimeter band in order to use all facilities effectively. This may mean eventually carrying the bulk of long-haul traffic in the millimeter-wave band via satellite and automatically switching high-precedence traffic to other circuits not affected by rainfall or temporarily providing other resources when a rain outage is momentarily encountered.

Even without switching, a millimeter-wave satellite system using proliferated terminals close to the end users probably could provide better performance for the average long-haul user for all classes of precedence than is being achieved in current military communication systems.

The Navy and Air Force are both developing equipment for experimental satellite links at the lower end of the millimeter band [33-36]. The concept of designing for higher outage than is currently the practice could be tested in these experimental links to establish long-term performance statistics and to verify the acceptability of such designs. These tests should be strongly encouraged to pave the way for operational implementation of the proposed concept at an early date. This could lead to an operational system within the next 10 years.

If the proposed concept is accepted, it could form the basis for use of a major portion of the millimeter-wave band (excluding only a few small intervals around molecular resonance lines). Although it permits communications almost anywhere in the millimeter-wave band, actual usage will depend on both international and domestic frequency allocations. This new approach may provide the incentive for obtaining adequate allocations in the millimeter-wave band—allocations which could provide enough capacity to permit a high growth rate in communications (commercial as well as military) over the next two to four decades. This growth would in turn provide incentive for the continued improvements and cost reductions in millimeter-wave hardware required to fully realize the potential benefits of communicating in this band.

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